75th MORSS CD Cover Page

712CD

For office use only 41205

UNCLASSIFIED DISCLOSURE FORM CD Presentation

12-14 June 2007, at US Naval Academy, Annapolis, MD

Please complete this form 712CD as your cover page to your electronic briefing submission to the MORSS CD. Do not fax to the MORS office.

Author Request (To be completed by applicant) - The following author(s) request authority to disclose the following presentation in the MORSS Final Report, for inclusion on the MORSS CD and/or posting on the MORS web site.

Name of Principal Author and all other author(s):
Mr. Randolph A. Jones
Mr. Burney McKinley
Ms. Lora Johnson

Principal Author's Organization and address:
US Army Engineer Research and Development Center
ATTN: R. Jones GMM Bld 3286
3090 Halls Ferry Road
Vicksburg, MS 39180

Phone:601-634-4145

Fax:601-634-3068

Email:randy.jones1@us.army.mil

Original title on 712 A/B: Vehicle Gap Analysis Program

Revised title: Vehicle Gap Analysis Program

Presented in (input and Bold one): (WG 10, CG___, Special Session ___, Poster, Demo, or Tutorial):

This presentation is believed to be:
UNCLASSIFIED AND APPROVED FOR PUBLIC RELEASE

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **01 JUN 2007**	2. REPORT TYPE **N/A**	3. DATES COVERED **-**

4. TITLE AND SUBTITLE **Vehicle Gap Analysis Program**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **US Army Engineer Research and Development Center ATTN: R. Jones GMM Bld 3286 3090 Halls Ferry Road Vicksburg, MS 39180**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADM202526. Military Operations Research Society Symposium (75th) Held in Annapolis, Maryland on June 12-14, 2007, The original document contains color images.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**UU**	**30**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

Vehicle Gap Analysis Program

US Army Engineer Research & Development Center

Military Operations Research Society
75th Symposium
June 12 – 14, 2007

Presented By:
Mr. Randy Jones
U.S. Army
Engineer Research and Development Center
Geotechnical and Structures Laboratory
Vicksburg, Mississippi

601.634.4145 randy.jones1@us.army.mil

Presentation Outline

- Introduction to ERDC mobility research
- Statement of research problem, objective and approach
- Simulation of terrain mechanics
- Terrain representation
- Terrain mechanics verification
- Where we're at now
- VAGP Interface
- Conclusions

ERDC's Mobility R&D Mission

The ERDC mobility research mission is focused on developing high resolution, component-level mobility representations that produce consistent single- and unit-level vehicle mobility in live, virtual, and constructive M&S environments.

Serving Joint Customers

Research Problem

- The Future Combat System Operational Requirements Document requires that manned and unmanned ground vehicles be capable of negotiating gaps 1.5- to 4.0-meters wide
- Current vehicle performance models lack the fidelity and accuracy to predict a vehicle’s capability to negotiate deformable gaps

Research Objective

- The objective of this research is to develop physics based simulation and analysis capabilities to accurately predict vehicles crossing deformable terrains
- Develop terrain mechanics models for use with on-board robotic vehicles for decision logic
- Develop tactical decision aides for maneuver support

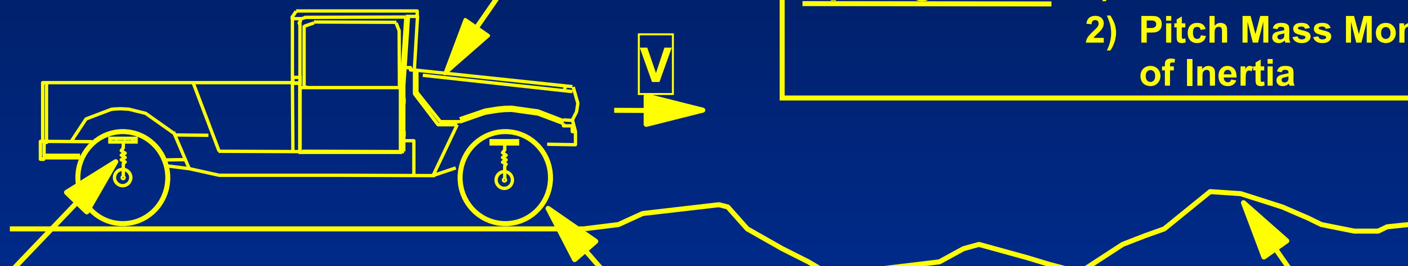
Research Approach

US Army Engineer Research & Development Center

- Use an existing vehicle dynamics software package to demonstrate research and develop new analysis tool
  – The 2-D Vehicle Dynamics (VehDyn II) software package distributed with the NATO Reference Mobility Model (NRMM) was selected as the demonstration platform
- Integrate existing terrain mechanics models
  – Use soils models developed for “whole” traction element representation
  – Use soils models dependent on standard military trafficability kits (hand-held cone penetrometer)
- Develop vehicle chassis and terrain contact interactions
- Develop a vehicle driver model based on the vehicle’s propulsion system

VehDyn II

US Army Engineer Research & Development Center



Sprung Mass: 1) CG Location
2) Pitch Mass Moment of Inertia

Terrain Profile: Non-deformable

Suspension Elements

1) Spring, Damper, Rotational Spring
2) Nonlinear, Hysteretic Relation with Straight-Line Transition
3) Independent, Walking Beam, Bogie, Caterpillar 30/30 Front End

Wheels/Tires: Continuous Spring Model

Tracked Vehicles: 1) Band Track Model
2) Mod. Interconn. Spg Model

Terrain Mechanics Model (Wheels)

- **The fundamental traction element forces for fine-grained and coarse-grained soils are estimated from specifically derived numerics**
- **The clay numeric (Π_C) is a function of the RCI, traction element nominal contact length and width; tire section width, diameter, and deflection**
- **The sand numeric (Π_S) is a function of the CI and a similar set of measurable traction element items**

$$\Pi_C = \frac{RCI(bd)}{w(1-\delta/h)^{3/2}(1+b/d)^{3/4}}$$

Fine-grained model

$$\Pi_S = \frac{CI(bd)^{3/2}}{w(1-\delta/h)^{3}}$$

Coarse-grained model

Where: *RCI*, *CI* = Soil strength
b = Tire section width
d = Nominal wheel diameter
h = Tire section height
δ = Tire deflection
w = Weight beneath tire

Terrain Mechanics Model (Wheels)

US Army Engineer Research & Development Center

- The numeric (Π) is combined with vehicle performance results to predict drawbar and motion resistance for fine- and course-grained soils

- The equations show the performance parameter as a coefficient based on the weight of the traction element

$$\frac{D}{w} = 0.5Log_{10}\left(i/i_{SP}\right), \quad i_{SP} = \frac{21}{\Pi_C^{5/2}}$$

Fine-grained $$\frac{R}{w} = \frac{12}{\Pi_C^{\ 2}} + .007$$

$$\frac{D}{w} = 0.52 - \frac{396}{\Pi_{DP} + 557}, \quad \Pi_{DP} = \Pi_S \frac{1}{j^{1/j}}$$

$$\frac{R}{w} = X_j + \sqrt{X_j^{\ 2} + .0000457\Pi_{Rj} + .008}$$

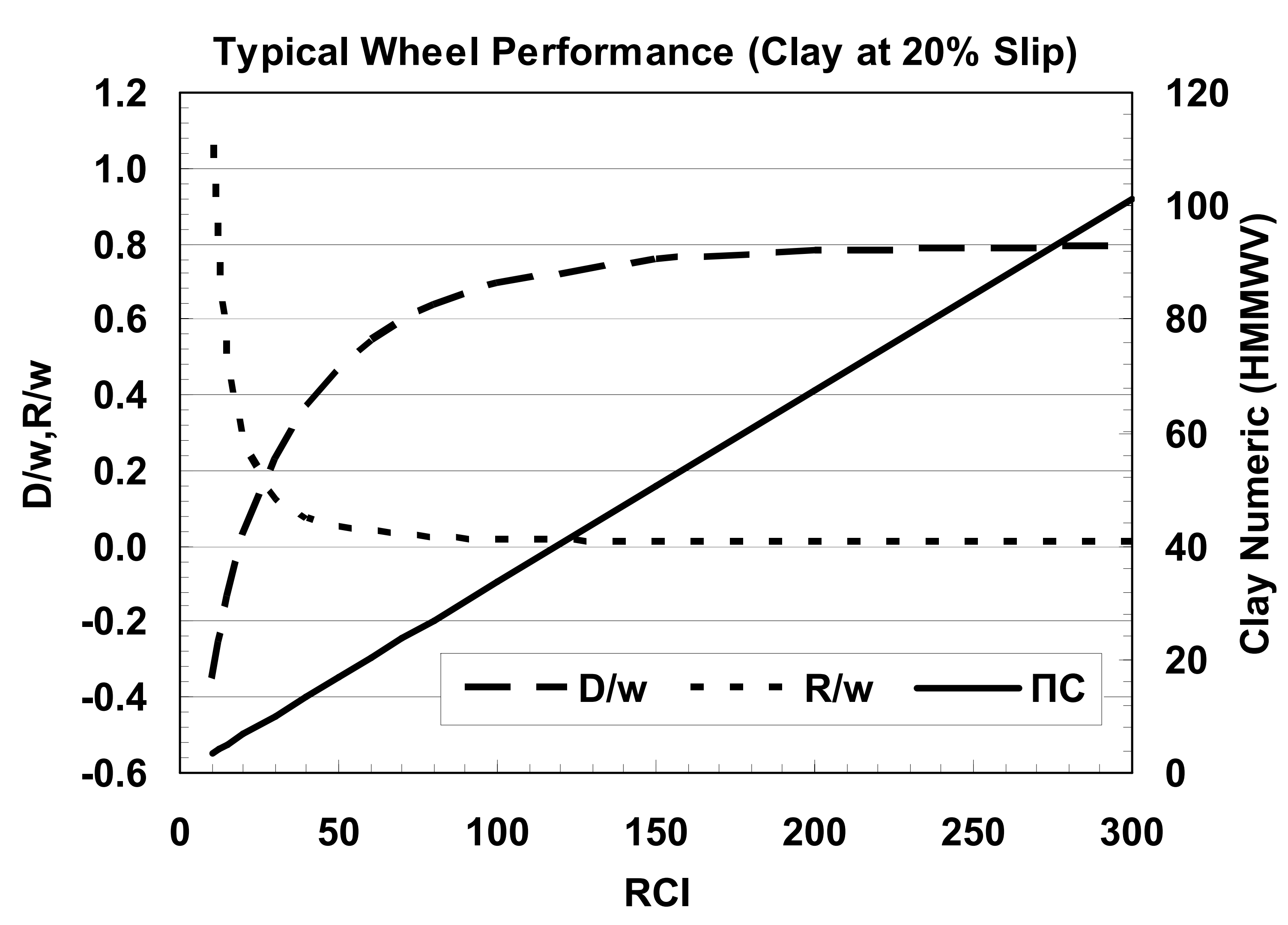
$$X_j = 0.44 - .002287\Pi_{Rj}$$

$$\Pi_{Rj} = \Pi_S \bullet \frac{j^{1/2}}{1 + b/d}$$

Course-grained

Terrain Mechanics Model (Wheels)

US Army Engineer Research & Development Center



Terrain Mechanics Model (Wheels)

- **A variant of the clay numeric (Π_{CZ}) and the sand numeric (Π_{SZ}) is used to estimate wheel sinkage**

$$\Pi_{Cz} = \frac{RCI\left(bd\right)}{w\left(1-\delta/h\right)^{3/2}}$$

Fine-grained sinkage

$$\frac{z_P}{d} = \frac{5}{\left(\Pi_{CZ} \Big/ \text{slip}_{SP}^{\,1/5}\right)^{5/3}}$$

$$Z_n = Z_1 \sqrt{n}$$

Sinkage for n vehicle passes

$$\Pi_{Sz} = \Pi_S \bullet \frac{1}{1+b/d}$$

Coarse-grained sinkage

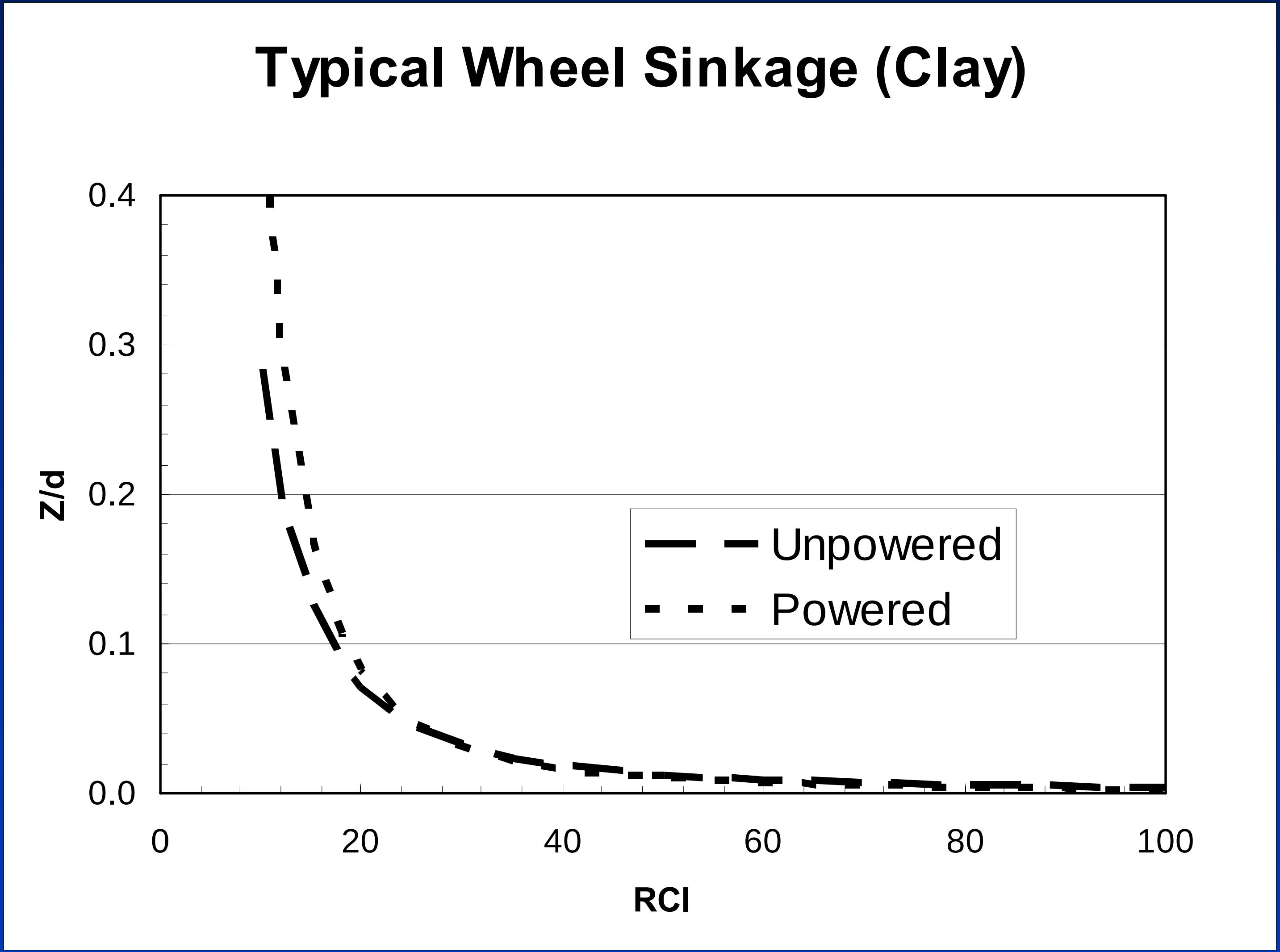
$$\frac{z_P}{d} = \frac{14}{\Pi_{SZ}}$$

$$Z_1 = \sqrt{Z_{U_1}^2 + Z_{P_1}^2 + Z_{U_2}^2 + \ldots + Z_{P_m}^2}$$

Sinkage for m traction elements

Terrain Mechanics Model (Wheels)

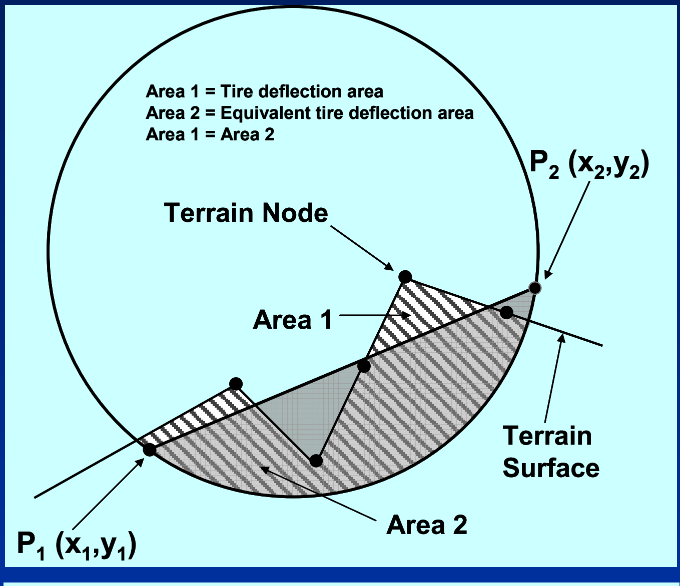
US Army Engineer Research & Development Center



Terrain Mechanics Model (Wheels)

US Army Engineer Research & Development Center

- The terrain is represented by a series of terrain nodes
- The traction element sinkage is determined and used to calculate the sinkage at the current time step that applies to each terrain node in contact with the traction element



$$S_c = (V \times T)/C \times S$$

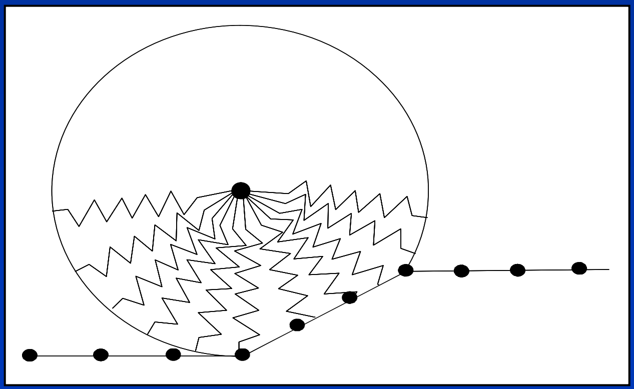
S = Predicted total sinkage (in) for entire wheel

C = Chord Length (in) from P1 to P2

T = Time step (sec)

V = Vehicle's instantaneous velocity (in/sec)

S_c = Sinkage (in) this time step



Continuous spring tire model and terrain nodes

Terrain Mechanics Model (Tracks)

US Army Engineer Research & Development Center

- **The fundamental traction element forces for fine-grained and coarse-grained soils are estimated from specifically derived numerics and empirical relationships**
- **The clay numeric (Π_C) is a function of the RCI, traction element nominal contact length and track width**
- **The sand numeric (Π_S) is a function of the CI and the same set of measurable traction element items**

$$\Pi_C = \frac{RCI(bl)}{w}$$

Fine-grained model

$$\Pi_S = \frac{G(bl)^{3/2}}{w}; \quad G = CI * 0.8645 / 3$$

Coarse-grained model

Where:

RCI,CI =Soil strength

G =Soil strength gradient

b =Track width

l =Nominal contact length (ground contact length)

w =Weight beneath track

Terrain Mechanics Model (Tracks)

US Army Engineer Research & Development Center

- A variant of the clay numeric (Π_C) and the sand numeric (Π_S) is used to estimate wheel sinkage

$$\frac{Z}{l} = 0.00443e^{\frac{5.887}{\Pi_C}}$$

Fine-grained sinkage

$$\frac{Z}{l} = 0.030292 + \frac{0.85437}{\Pi_S} - \frac{0.48443}{\Pi_S{}^2}$$

Coarse-grained sinkage

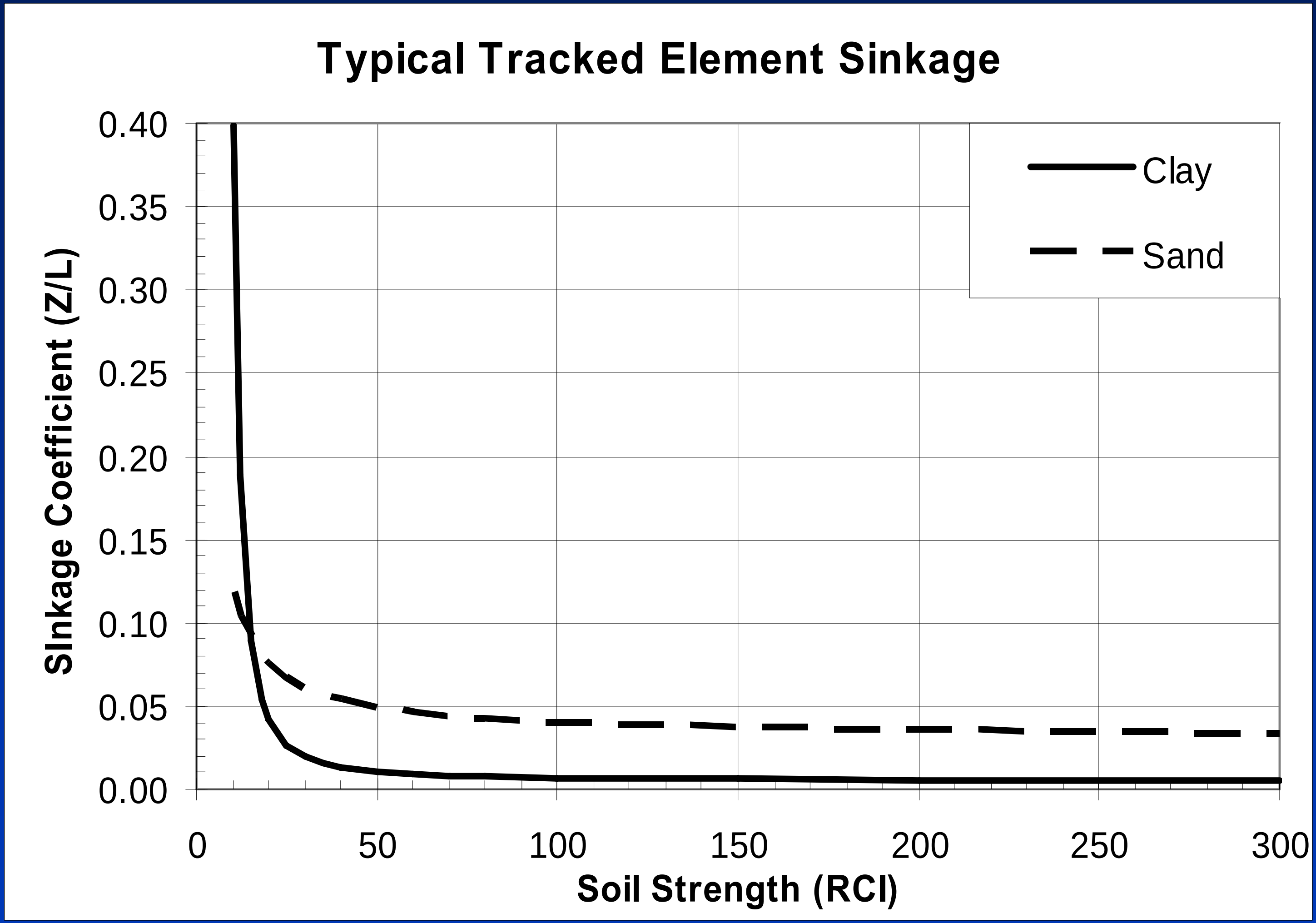
$$Z_n = Z_1 \sqrt{n}$$

Sinkage for n vehicle passes

$$Z_1 = \sqrt{Z_{U1}^2 + Z_{P1}^2 + Z_{U2}^2 + \ldots + Z_{Pm}^2}$$

Sinkage for m traction elements

Terrain Mechanics Model (Tracks)



Terrain Mechanics Model (Tracks)

US Army Engineer Research & Development Center

- Drawbar pull for fine-grained soils are calculated using tracked vehicle empirical relationships
- The sand numeric (Π) is combined with vehicle performance results to predict drawbar for course-grained soils
- The equations show the performance parameter as a coefficient based on the weight of the traction element

$$\frac{D}{w} = A + \frac{B}{RCIx + C}$$

	A	B	C
FGa	0.7814494	-6.709946	7.854210
FGb	0.8117813	-5.737010	6.507696
CPF<4	0.8476903	-4.974673	5.724387

FGa =CPF≥4, USCS: ML, CL, MLCL, OL, SM, SMSC, GM
FGb =CPF≥4, USCS: SC, GC, CH, MH, OH

Fine-grained

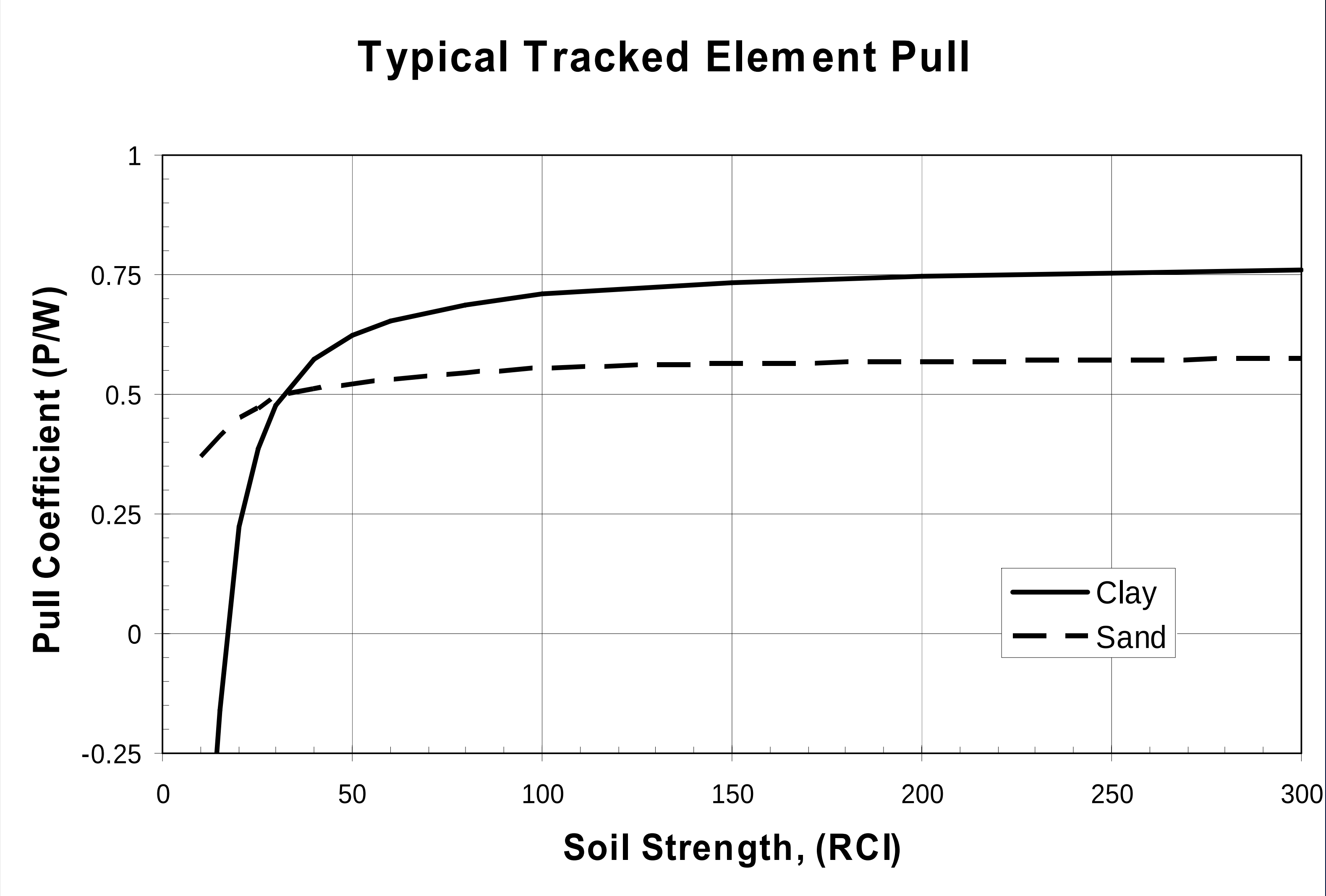
$$\frac{D}{w} = k1 + k2\log_{10}(\Pi_S)$$

k1	k2	Condition
0	0	$\Pi_S \leq 0$
0.121	0.258	$0 < \Pi_S \leq 25$
0.339	0.109	$25 < \Pi_S \leq 100$
0.481	0.038	$100 < \Pi_S \leq 1000$
0.595	0	$\Pi_S > 1000$

Track Type	Max
Flexible	0.3926
Girderized	0.5365

Course-grained

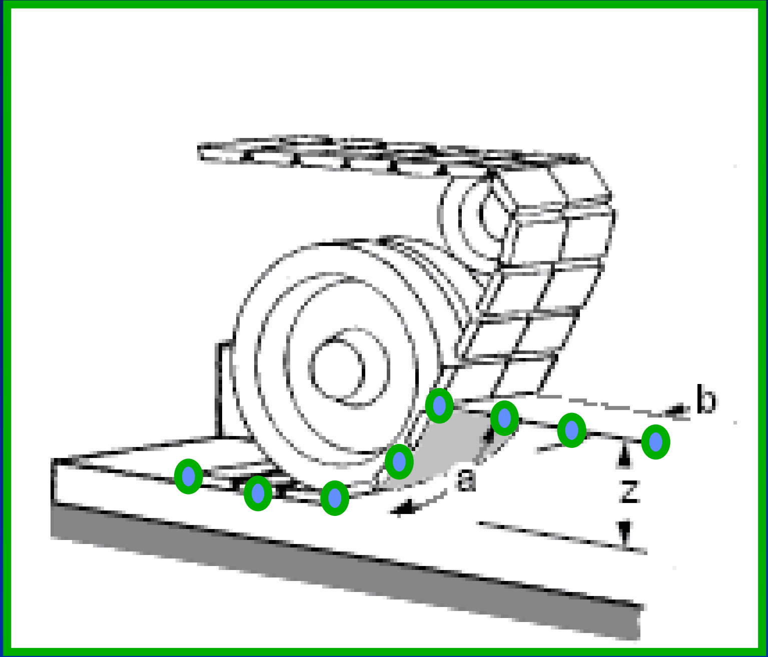
Terrain Mechanics Model (Tracks)

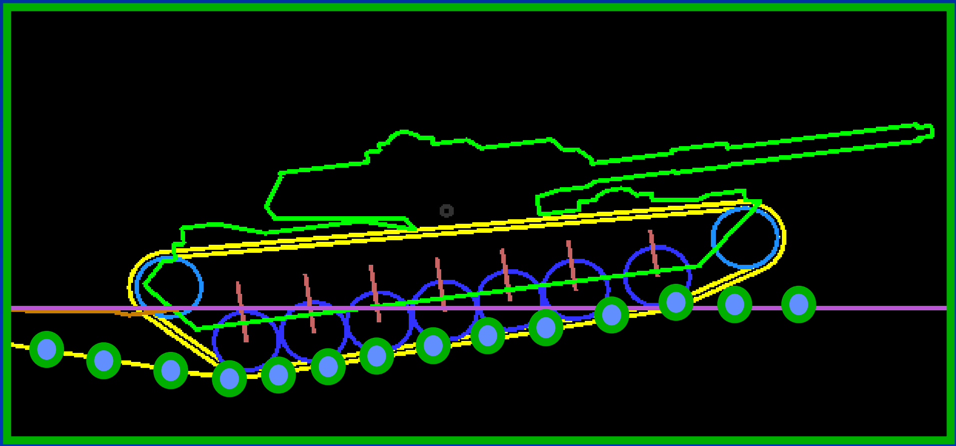


Terrain Mechanics Model (Tracks)

US Army Engineer Research & Development Center

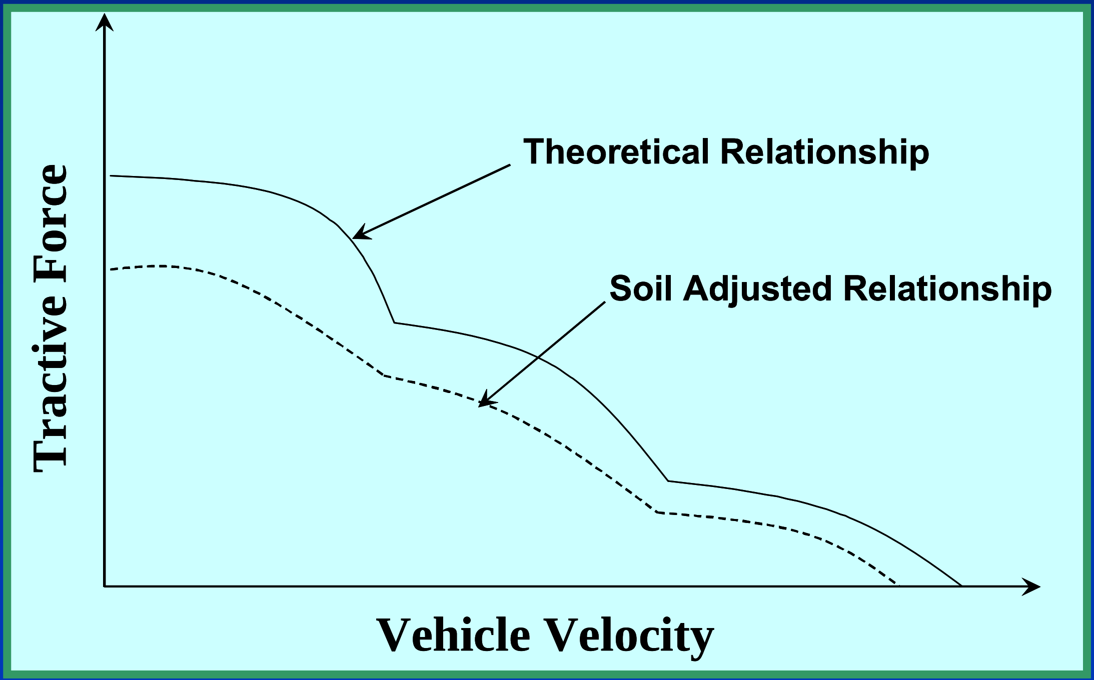
- The terrain is represented by a series of terrain nodes
- The traction element sinkage is determined and used to calculate the sinkage at the current time step that applies to each terrain node in contact with the traction element





Vehicle Traction

- The vehicle traction is determined by using the theoretical tractive force and speed relationship developed from the vehicle's propulsion system
- It is adjusted based on the soil properties and numeric relationships

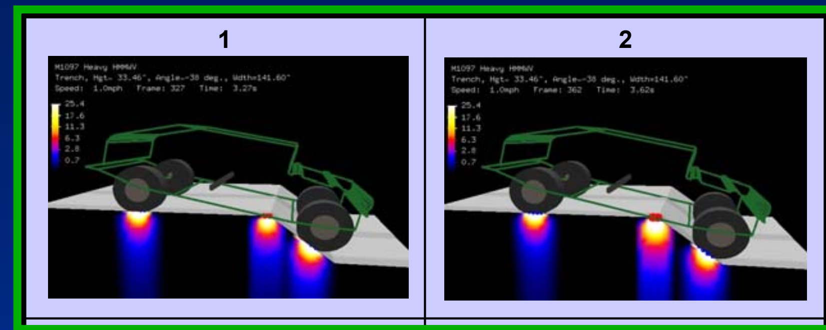


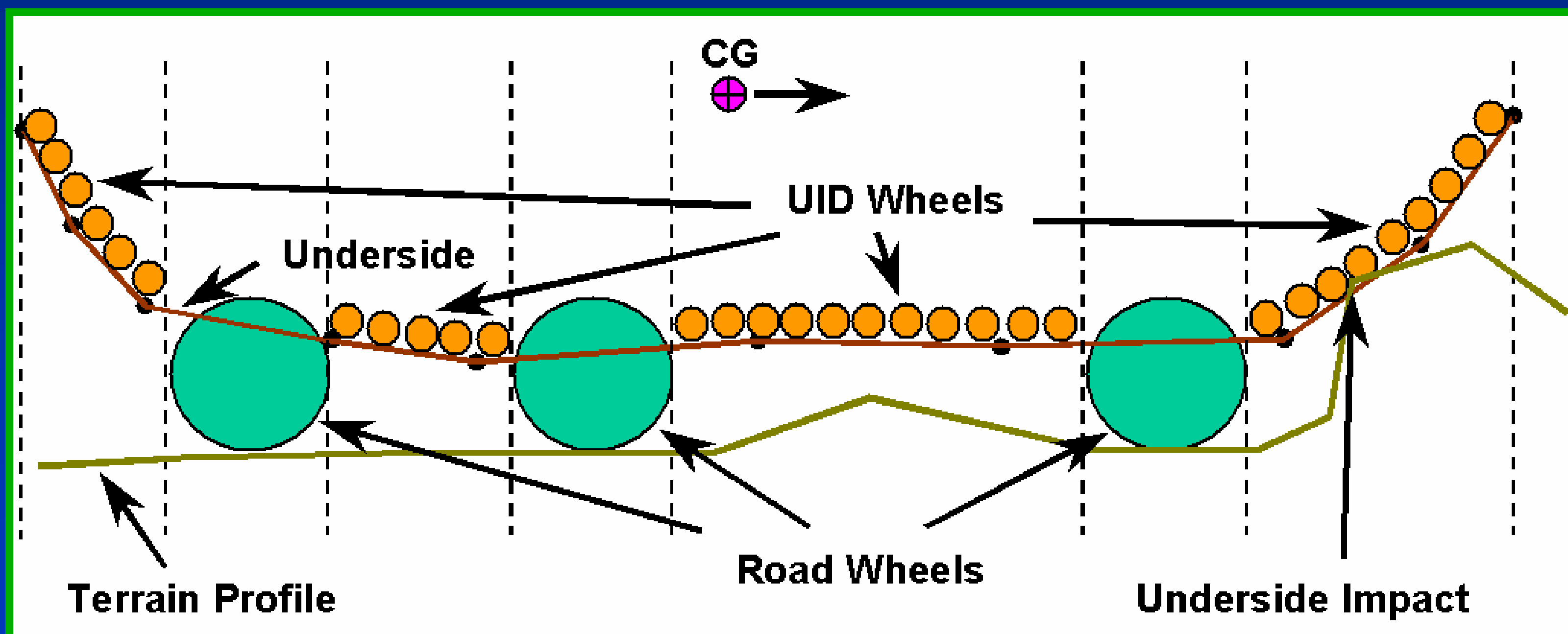
US Army Engineer Research & Development Center

Chassis/Terrain Interaction

US Army Engineer Research & Development Center

- Underside Impact Detection (UID) "drag" wheels placed all along vehicle underside
- Await impact with the ground
- Produce normal and tangential (drag) forces applied to chassis
- Applied laterally across half the vehicle width like long "tubes"





Gap Crossing Verification

US Army Engineer Research & Development Center

- Vehicle accelerates to 2 mph
- Chassis changes color based on tractive force relationship
- Terrain deformation indicated by different colored lines

ERDC

VCI Verification

US Army Engineer Research & Development Center

- Vehicle accelerates to 10 mph
- Chassis changes color based on tractive force relationship
- Terrain deformation indicated by different colored lines

Hard Surface Slope Verification

- **DB = Drawbar**
  - **Drawbar pull relationship is used to calculate the "theoretical" maximum slope**

Slope Climbing (Percent)		
Vehicle	***VGAP***	***DB Slope***
M1097 (HMMWV)	81.6	75.5
M1078 (LMTV)	81.3	75.5
LAV	75.8	75.4
M923	68.0	73.5
M977 (HEMTT)	63.7	74.9
M113	81.6	104.2
M2A2 (BFV)	73.4	104.3
M1A1	78.5	104.1

Fine Grain VCI1 Verification

- **Vehicle Cone Index x (VCIx) is the minimum soil strength required to support the vehicle for x number of passes**
- **Soil strength is measured in terms of Remolded Cone Index (RCI)**
- **Typical field test variation is +/- 3 RCI points**
- **NRMM is a validated vehicle model for calculating VCIx**

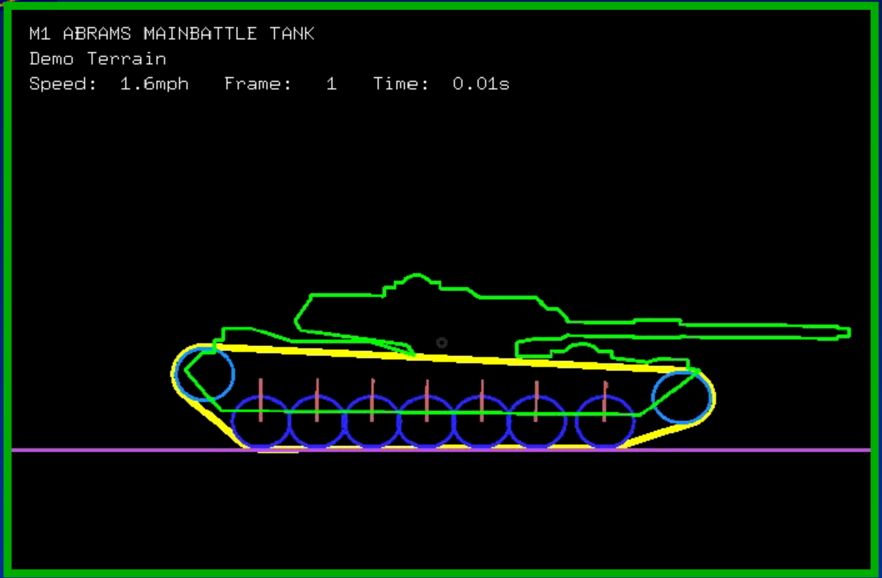
Computed Fine Grain VCI1		
	VGAP	**NRMMII**
M1097 (HMMWV)	20	22.2
M1078 (LMTV)	26	27.1
LAV	32	30.2
M923	17	29.7
M977 (HEMTT)	33	32.1
M113	16	15.2
M2A2 (BFV)	20	18.5
M1A1	26	25.3

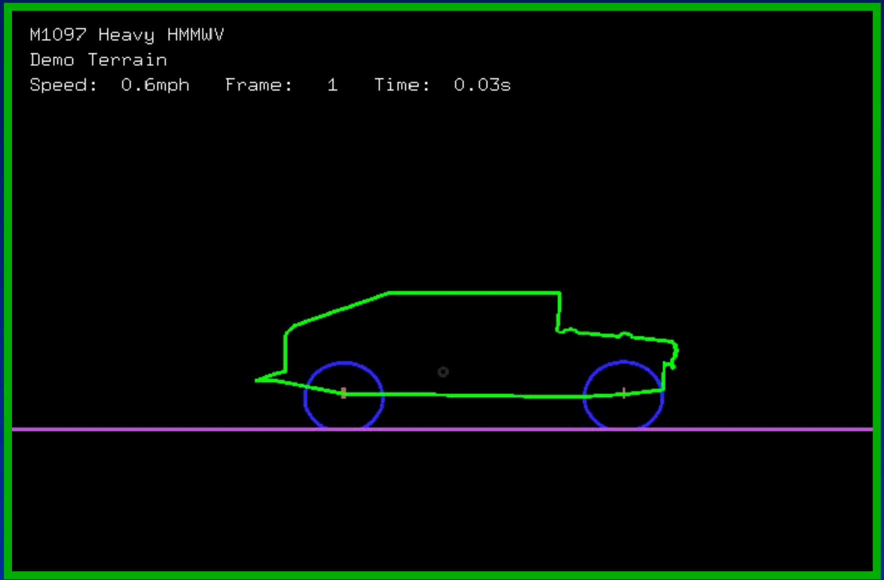
Coarse Grain VCI1 Verification

- **Vehicle Cone Index x (VCIx) is the minimum soil strength required to support the vehicle for x number of passes**
- **Soil strength is measured in terms of Cone Index (CI)**
- **Typical field test variation is +/- 3 RCI points**
- **NRMM is a validated vehicle model for calculating VCIx**

Computed Coarse Grain (SP) VCI1		
	VGAP	NRMMII
M1097 (HMMWV)	47	33.6
M1078 (LMTV)	58	46.1
LAV	70	66.2
M923	47	51.4
M977 (HEMTT)	32	40.5
M113	1	0.4
M2A2 (BFV)	1	0.3
M1A1	1	0.4

Where We're At Now

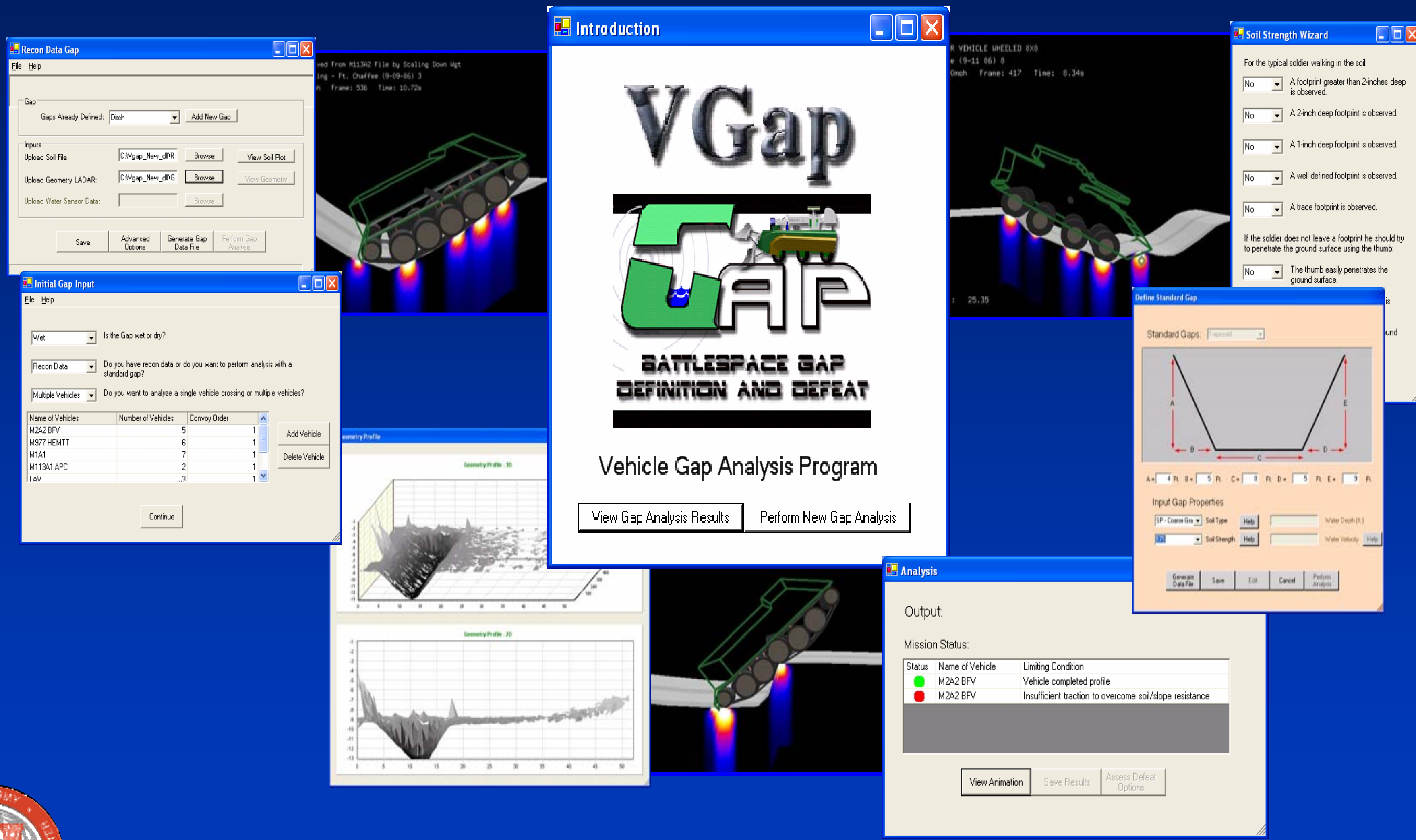




- Tire/Track interaction with deformable soil relationships based on soil type and strength
  - Soil strengths changes along the simulated profile
- Vehicles are driven by soil adjusted tractive-force relationship
- Variable forward acceleration
- Vehicle Underside Impact Detection

VGAP Interface

US Army Engineer Research & Development Center



One Corps, One Regiment, One Team . . . Serving Soldiers, the Army, the Nation

Conclusions

US Army Engineer Research & Development Center

- A set of equations and methodologies have been presented that were used to create a new vehicle mobility analysis tool
- This terrain mechanics modeling approach is based on algorithms for whole wheel tests (soil bin) and full vehicle field tests
- This approach is expected to yield representative performance (longitudinal traction, resistance and sinkage) for vehicles in a dynamic simulated environment
- The terrain mechanics model is applicable to a variety of simulation environments and on-board robotic decision logic